LAPPD as a timing layer for the LHCb ECAL in Upgrade2

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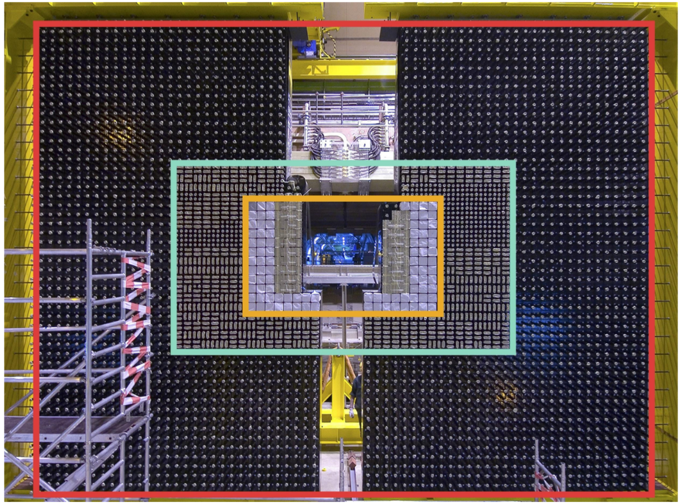
Workshop on picosecond timing detectors for physics – Zurich, 11th September 2021

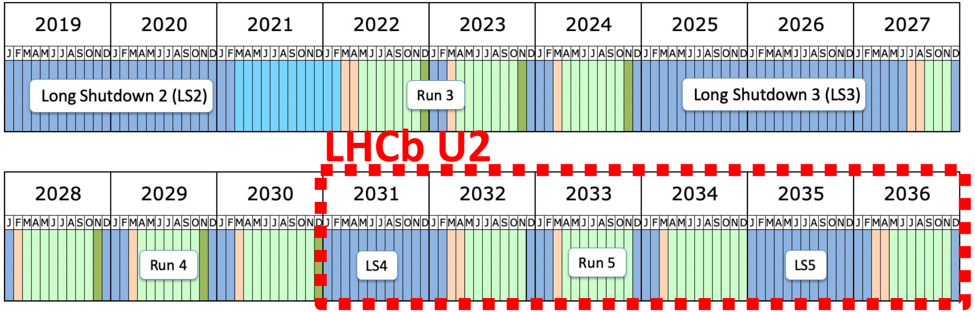
Outline

- General introduction on current ECAL and plans for a timing layer for LHCb ECAL-U2
- The Large Area Picosecond PhotoDetector (LAPPD)
- Results of tests conducted on two LAPPDs
  - Laboratory tests with pulsed laser
  - Results at DESY beamtest facility
- Wrap-up and conclusions

Current and future ECAL

- Large array of shashlik cells optimised for π^0, γ and $e^{\pm}$ in the few-GeV up to 100-GeV region at **L = 2 x 10^{32} $cm^{-2}s^{-1}$**
  - Radiation tolerance up to 40 kGy
  - Three regions with different cell size: 4x4, 6x6, 12x12 cm^2
  - Energy resolution: $\frac{\sigma(E)}{E} \approx \frac{10\%}{\sqrt{E}} \oplus 1\%$
- ECAL will be rebuilt during **LS4** with radiation tolerant modules and refurbished old modules
  - Instantaneous luminosity up to **1.5 x 10^{34} $cm^{-2}s^{-1}$**
  - Total integrated dose up to **1 MGy** and **6 x 10^{16} 1Mev neq/cm^2**
  - Increase granularity to cope with occupancy
  - **Use time information to discriminate pp collisions with resolution of O(10) ps**

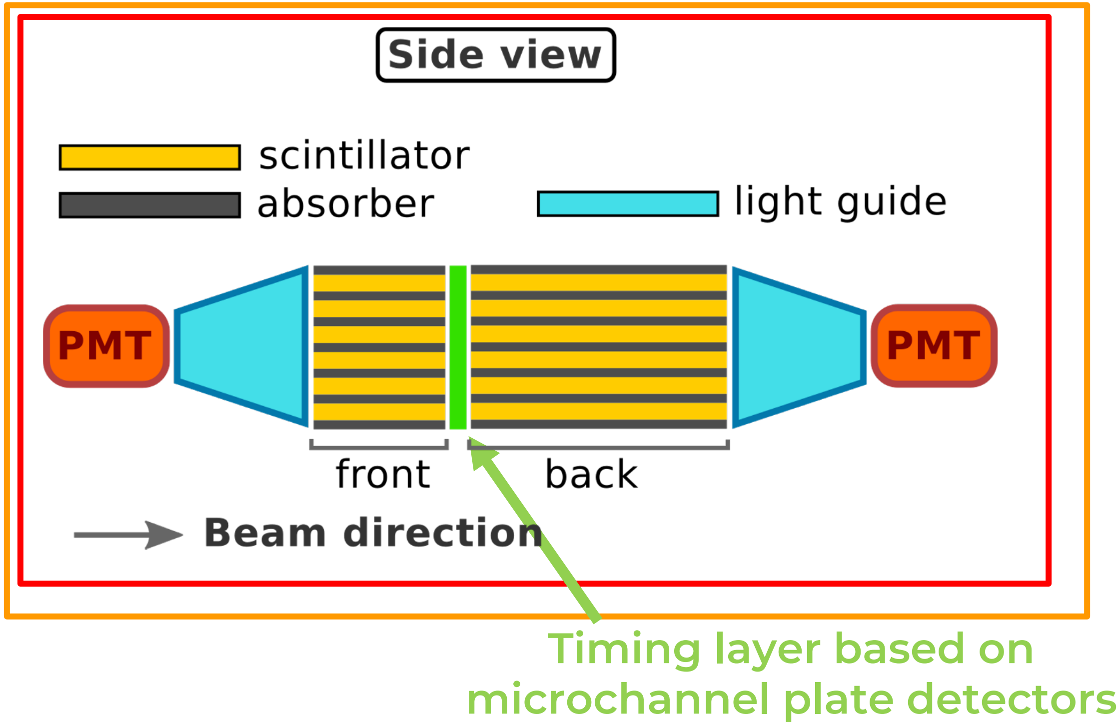




See Loris Martinazzoli's talk from yesterday

A timing layer for the LHCb U2

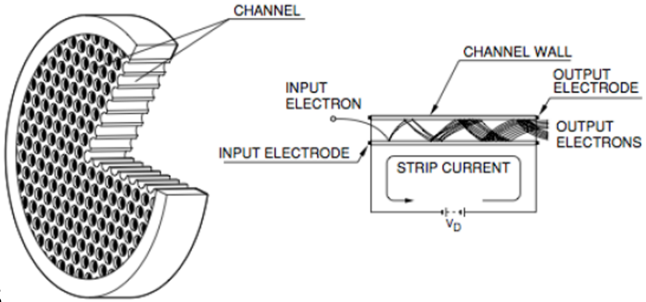
See Loris Martinazzoli's talk from yesterday morning for more details on the calorimeter technology



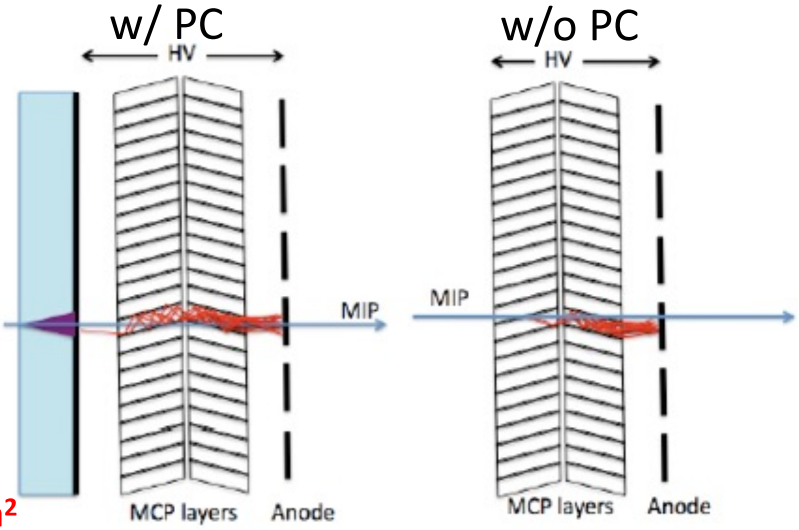
Place a thin detector based on MCP-PMT between two sections of double readout sampling calorimeter split at the shower maximum to sample the secondary particles produced in EM showers

Why Microchannel plates

- A microchannel plate (MCP) is an array of miniature electron multipliers
  - Typical diameters (d) of micropores in the range 6-25 μm, with thickness (L) of 0.4-1 mm
  - Very large S/N thanks to gain of O(10^3) for single MCP
    → **excellent time resolution**



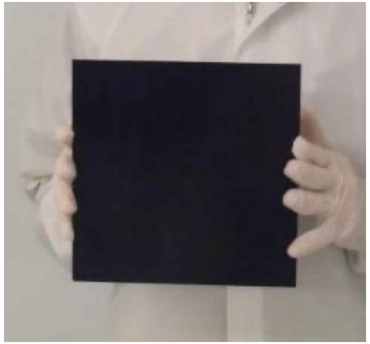
- Original idea to use them for sampling EM showers dates back to the '90s
  - A. I. Ronzhin et al., IFVE 90-99, Protvino, 1990
  - Recent work focused on Phase-2 HL-LHC upgrades
    ➔ A. Bornheim , A. Ronzhin et al.;
    ➔ A. Barnyakov, M. Barnyakov, T. Tabarelli de Fatis et al.

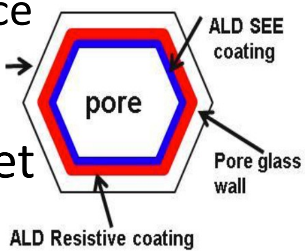


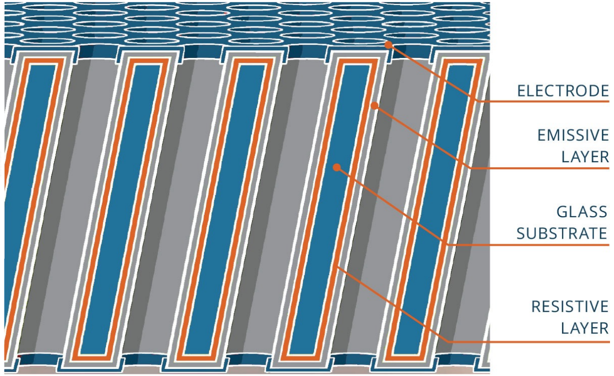
- Large number of secondary particles in the shower improves detection efficiency
  - **Possibile to avoid using a photocathode**
    ➔ primary electrons produced by ionisation inside the MCP
    ➔ great reduction of costs and assembly complexity
- **But need to withstand emitted charges up to hundreds of C/cm²**

The Large Area Picosecond PhotoDetector

- Developed by the LAPPD collaboration and commercialized by Incom Inc.
- MCP wafers made of commercial borosilicate glass with atomic layer deposition (ALD) of resistive and emissive layers
  - **ALD enhances emissivity** and is also predicated to prolong lifetime of the device
- Pore sizes of 10-20μm
- **Largest MCP-PMT** available on the market
  - wafer sizes up to 20x20 cm^2

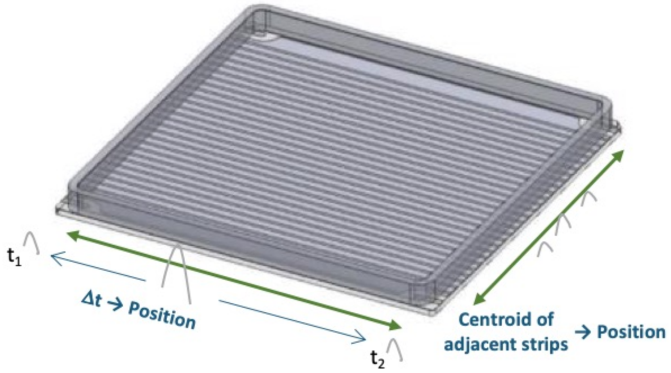






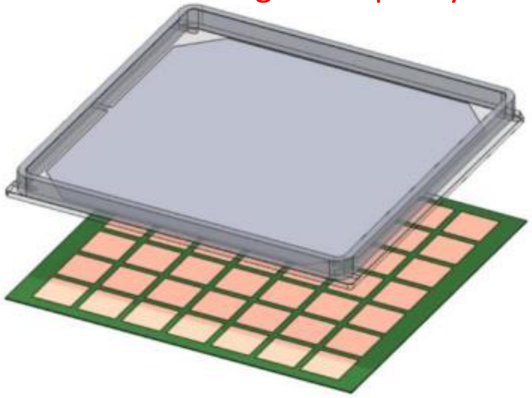
Two LAPPD versions

Gen-I: Direct read-out with strip-line anode with ~1 mm spatial resolution



Gen-II: Resistive interior anode with capacitively coupled external anode PCB with customizable pixel pattern

More suitable for high-occupancy environment

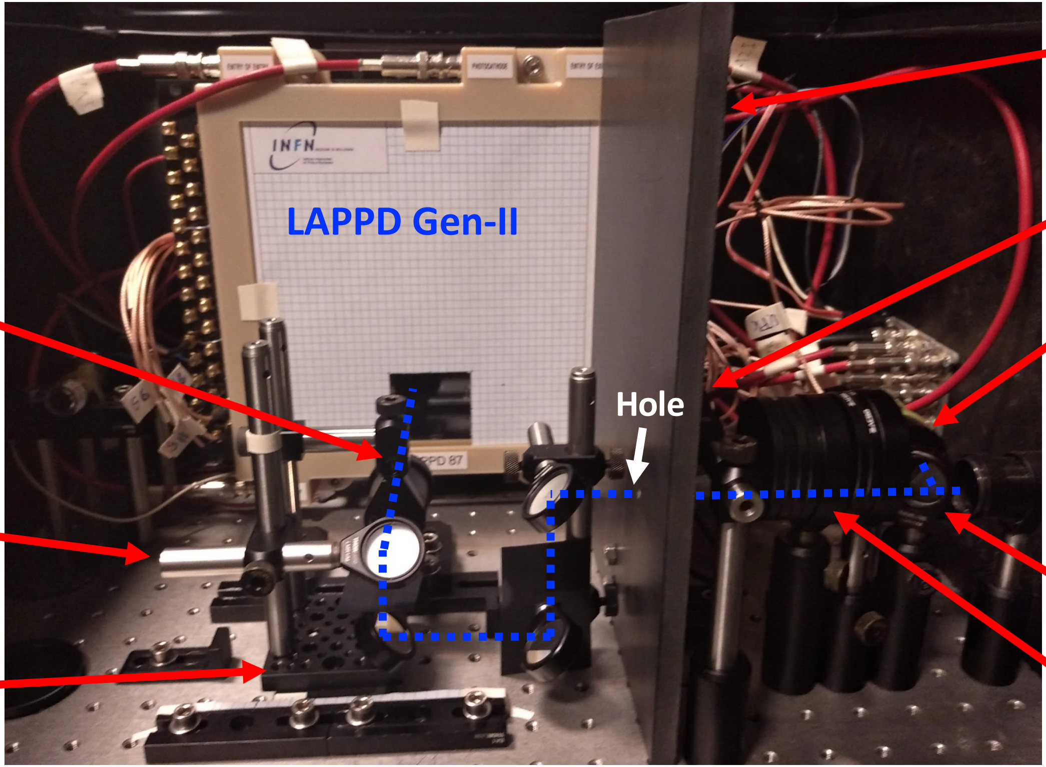


- Received both versions
  - Both with a stack of 2 MCPs with **20 μm pore size**
  - Intensive test program conducted in the laboratory with pulsed laser
  - Two beamtest conducted at DESY with 1 - 5.8 GeV electron beam

    ➔ **LAPPD inserted between front and back section of LHCb ECAL-U2 prototype**

Laboratory tests

Experimental setup



Beam diffuser and shutter

Upper mirror can be moved for vertical translations

Two of the mirrors movable on rail for horizontal translations

Screen to separate high from low luminous regions

Retractable calibrated Si photodiode

UFK-5G-2D

Laser head

Beam splitter

ND filters

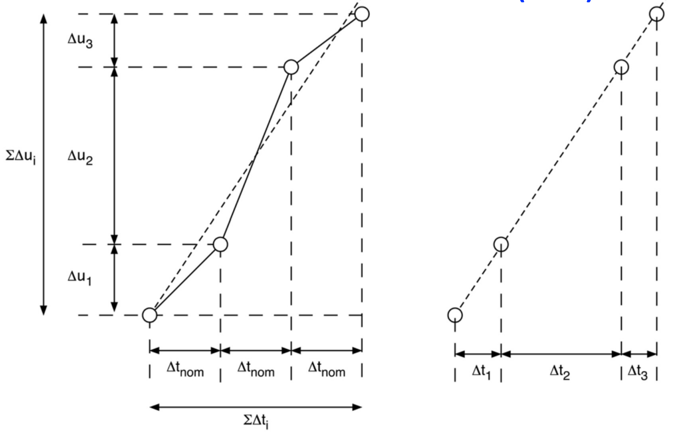
Experimental setup

- Laser system
  - PICOPOWER™-LD by ALPHALAS
  - Class 3B with **405 nm** wavelength
  - Repetition rate tunable from **1 Hz to 50 MHz** (in steps of 1 Hz)
  - Pulse width with optimal settings measured at the factory before shipment **11.7 ps (RMS)**
  - Trigger jitter measured in the lab to be **3.4 ps**
- Digitiser CAEN v1742
  - VME board with 32 channels based on the **DRS4 chip**
  - Maximum sampling rate is **5 GS/s** with 1024 cells per channels (full acquisition window of 204.8 ns), and **500 MHz** bandwidth
  - Unsatisfactory factory calibration → thoughroughly calibration perfomed in the lab based on **D. Stricker-Shaver et al. IEEE Trans. Nucl. Sci. 61 (2014) 3607** with a small modification (not discussed here)

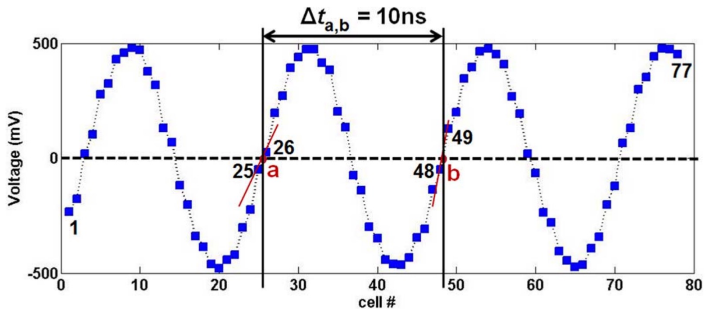
Digitiser calibration

D. Stricker-Shaver et al. IEEE Trans. Nucl. Sci. 61 (2014) 3607

- Voltage offsets calibration
  - Injected into each channel a set of **constant voltages**
  - Use a **linear fit** to parameterise the correspondence between voltage and the average or registered ADC counts for each cell of each channel



- Local calibration of cells time widths
  - Injected into each channel **50 MHz saw-tooth waveform**
  - Exploit **linear correlation between voltage difference and time difference of two adjacent cells**

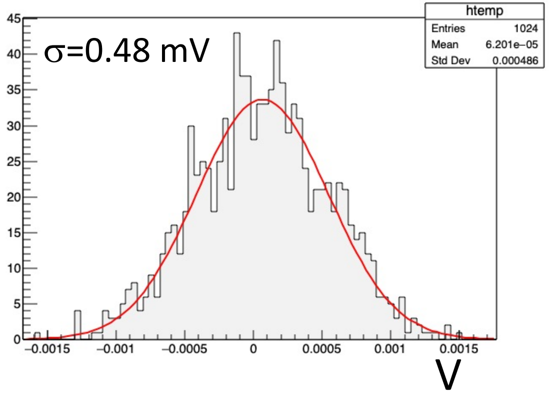


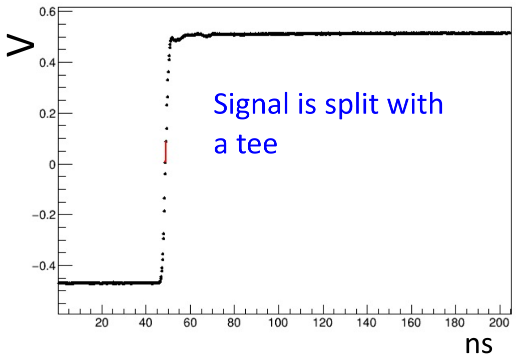
- Global calibration of cells time widths
  - Injected into each channel a **100 MHz sinusoid waveform**
  - Measure the time **difference between zero crossings** for one or multiple periods, and use this difference to correct the time widths of all intermediate cells

Goodness of calibration

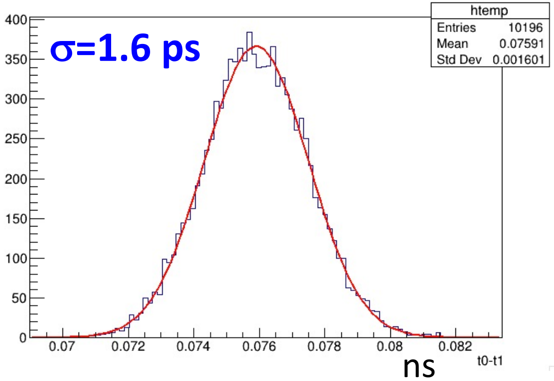
- Calibration check is performed with a **signal split test**
  - A rising edge is generated via waveform generator, split in two and sent to two distinct channels of the board
  - One of the two signals is also delayed wrt the other via a longer cable
    - Effect of small miscalibrations of cells widths adds up for signals separated in time
  - Difference between the two signals is used to determine time resolution

Residual noise after calibration

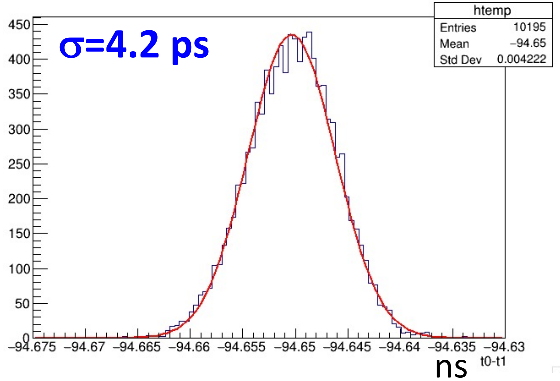




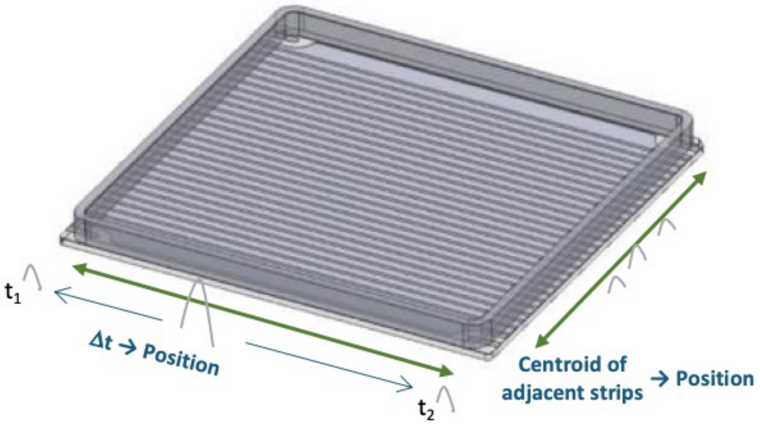
Signals not separated in time



Signals separated by ~100 ns

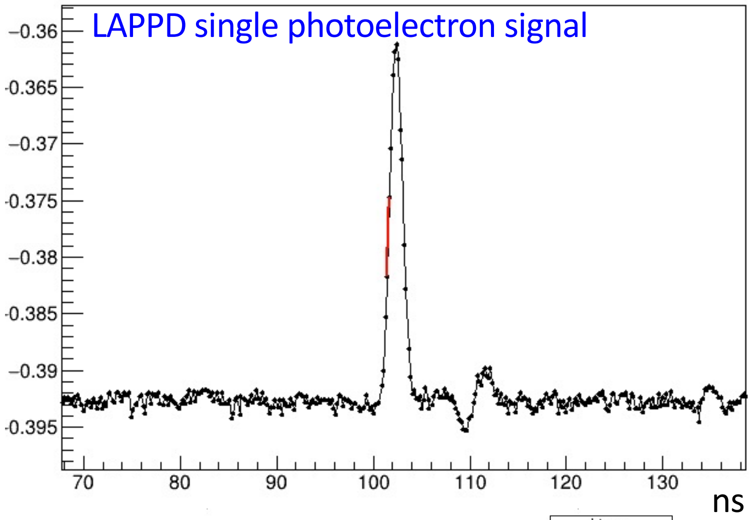


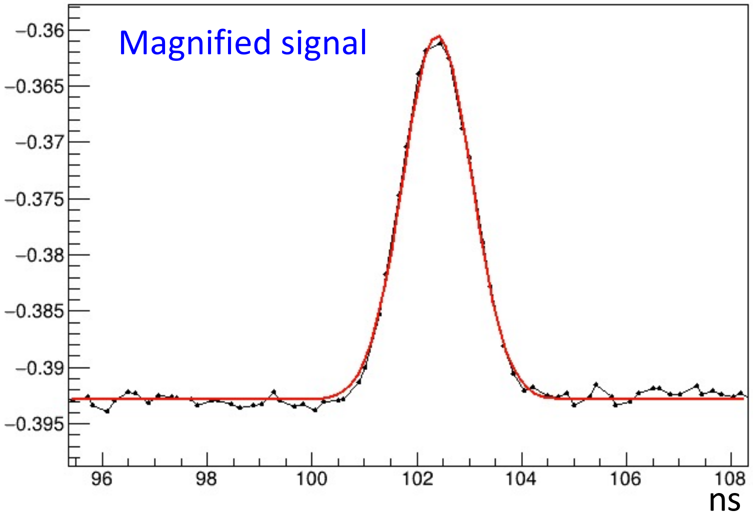
LAPPD Gen-I

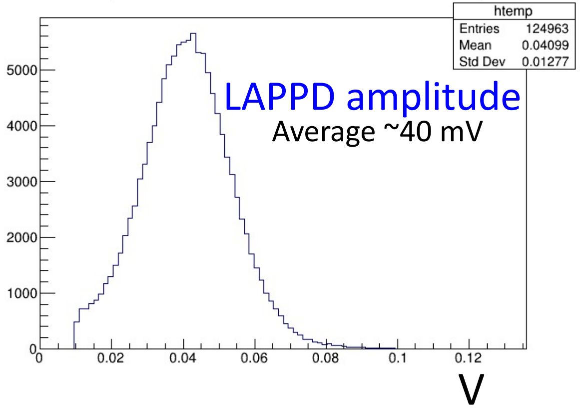


Reminder: anodic strip readout

LAPPD Gen-I: single PE signals





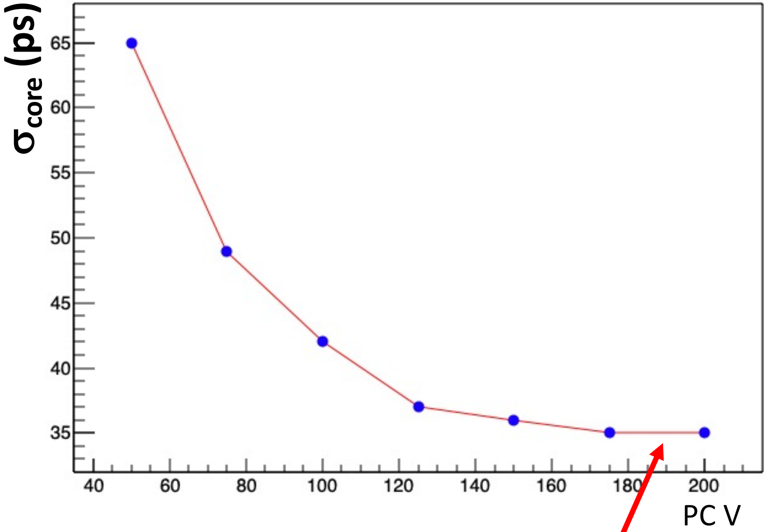


Voltage settings:

- 75V between photocathode top MCP
- 900V between the two faces of top MCP
- 200V in the inter-MCP gap
- 900V between the two faces of bottom MCP
- 200V between bottom MCP and anode

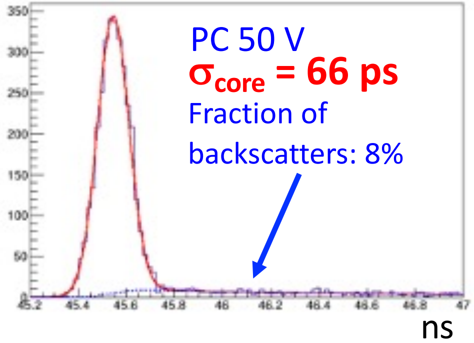
LAPPD Gen-I: single PE time resolution

- Long tail due to photoelectrons backscattering in the interstices between pores on the surface of the MCP, then landing again on the MCP after some time
  - **Not present when operating with inhibited PC**
- Time difference with respect to trigger is modeled with gaussian plus explonential tail convolved with gaussian
- Different settings of photocathode bias are tested
  - **Dependence of σ_{core} from PC bias**
  - Increasing fraction of **backscattered PE from 8% to 29%** with PC bias



Only core resolution, ignoring the backscattering tail

$t_{strip} - t_{trigger}$



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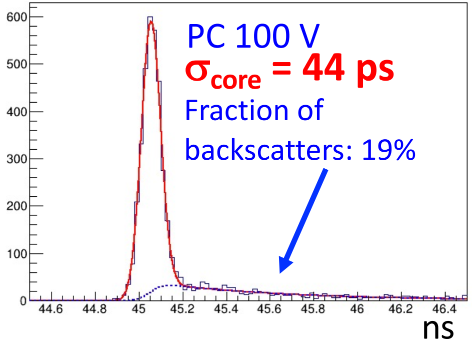

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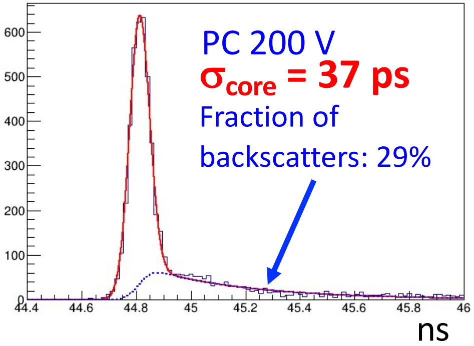
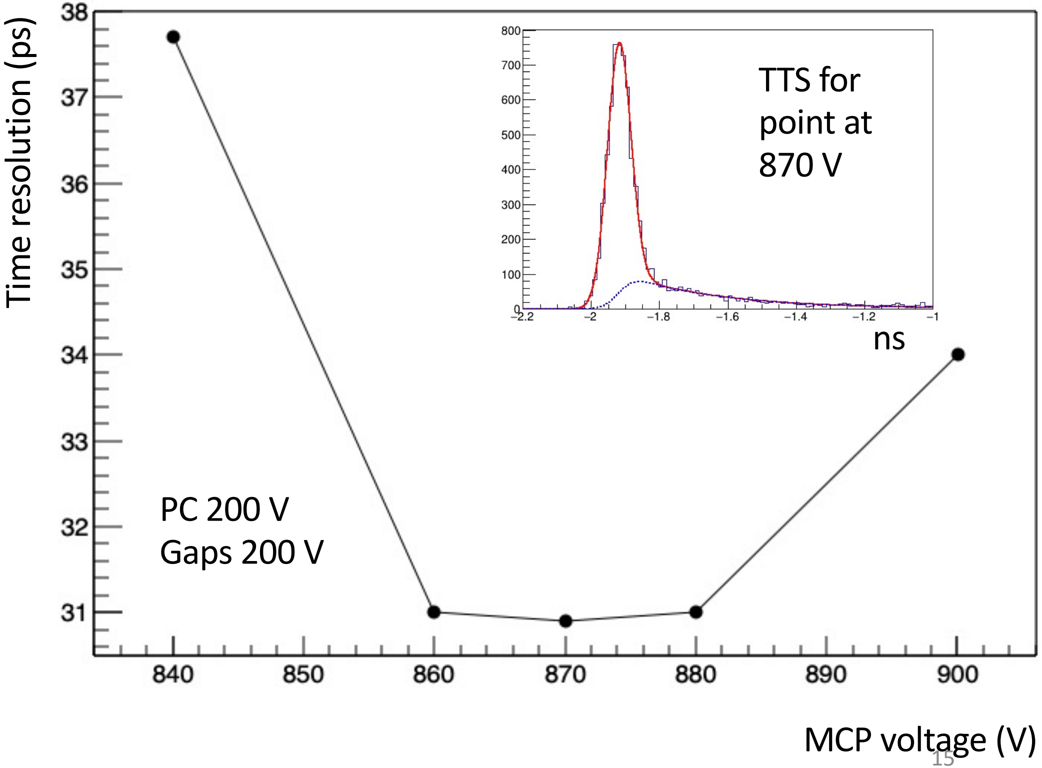


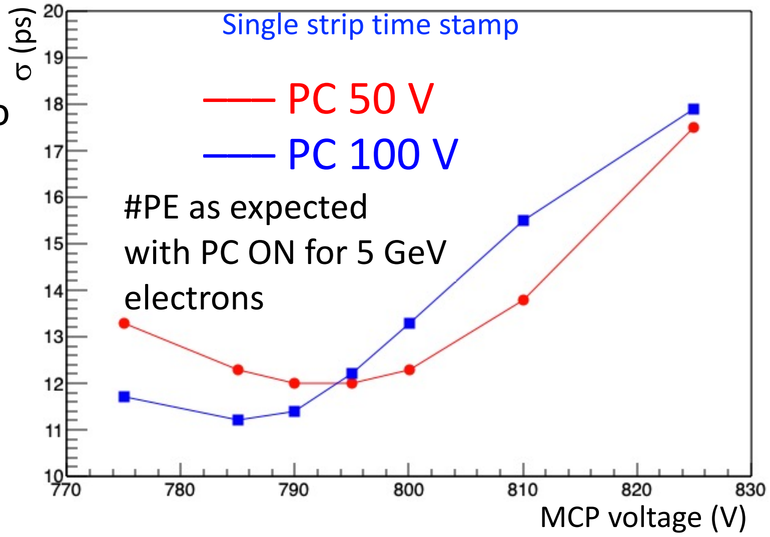
LAPPD Gen-I: single PE time resolution

- Scan of time resolution as a function of MCP bias
  - PC bias fixed to 200 V
  - Optimal MCP voltage around 870 V per MCP
  - **Best σ_{core} = 31 ps**



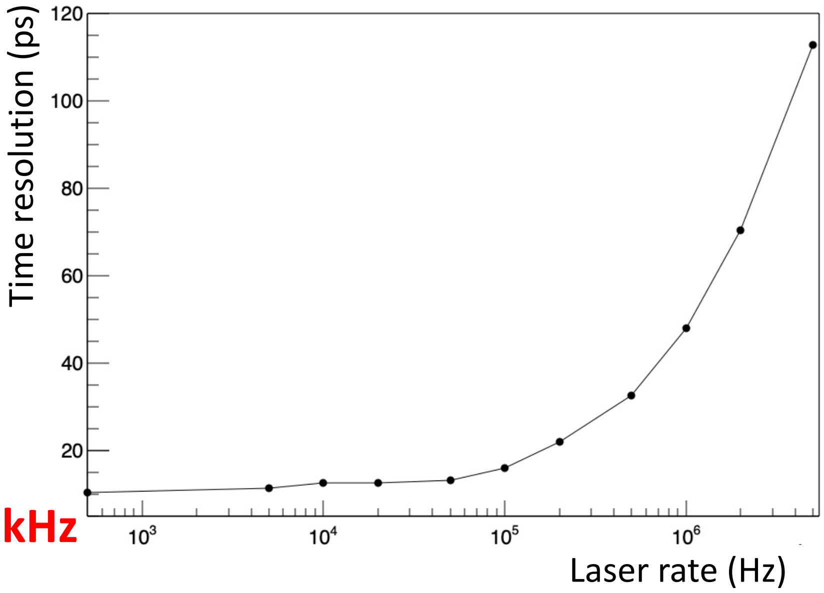
LAPPD Gen-I: expectations for beamtest

- Accurate simulations are used to predict the distributions of PEs produced when the LAPPD is placed at the maximum of an EM shower of 5 GeV electrons (DESY testbeam conditions)
  - Laser is defocused using a lens to reproduce the spatial distribution of PEs from EM shower (15 mm Ø)
- Optimal working point depends on two factors
  - **PC bias**: influences fraction of backscattering PE but also TTS from PC to first MCP
  - **MCP bias**: influences gain introducing saturation effects inside the pores
- **No trivial interplay between PC and MCP biases**
- Not taking into account
  - **Large fluctuations** of particles in the EM shower
  - **Time-spread** of particles in the EM shower



LAPPD Gen-I: repetition rate

- Frequency of pulsed laser is varied between **few hundreds of Hz up to 5 MHz**
  - PC: 50 V; MCP: 800 V; Gap; 200 V
- Laser beam spot **mimic EM shower of 5 GeV electrons**
- Signal amplitude (not shown here) is strongly reduced at the higher rates
- **Strong degradation of time resolution after 100 kHz**



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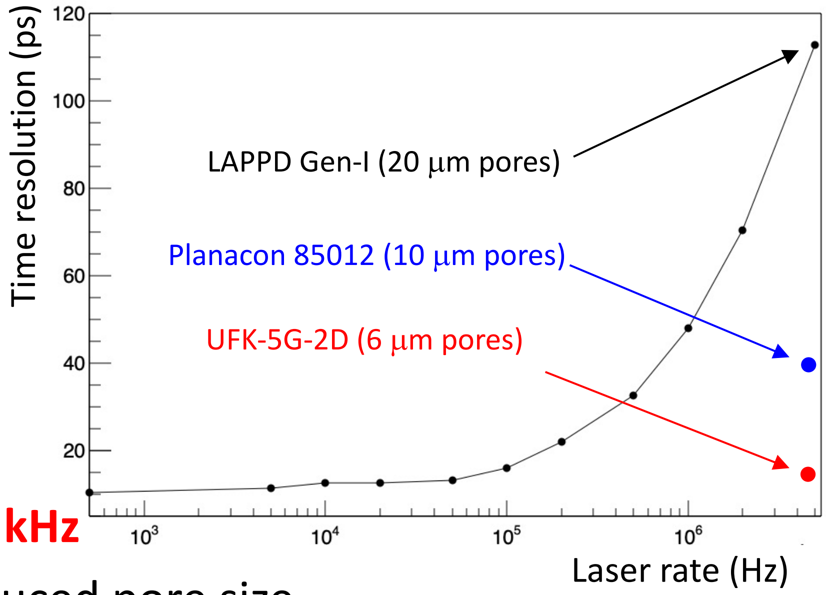
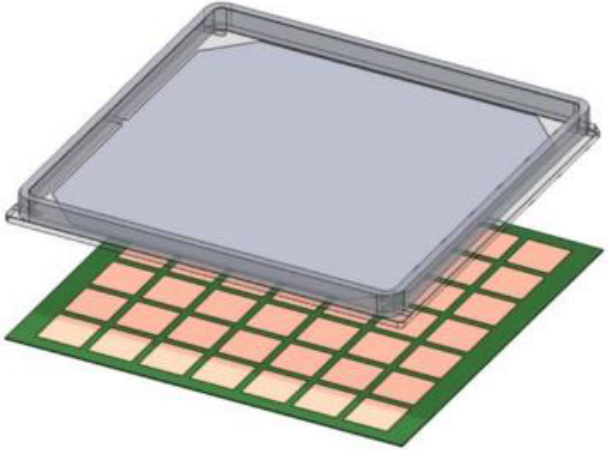


- **Strong degradation of time resolution after 100 kHz**
- Performances would benefit from MCPs with reduced pore size
  - Test repeated with two different MCP-PMT without any particular optimisations
    - ➔ Photonis Planacon 85012 with 10 μm pore size
    - ➔ LLC Katod UFK-5G-2D with 6 μm pore size
- Incom alredy produce LAPPD equipped with MCP with 10 μm pore size

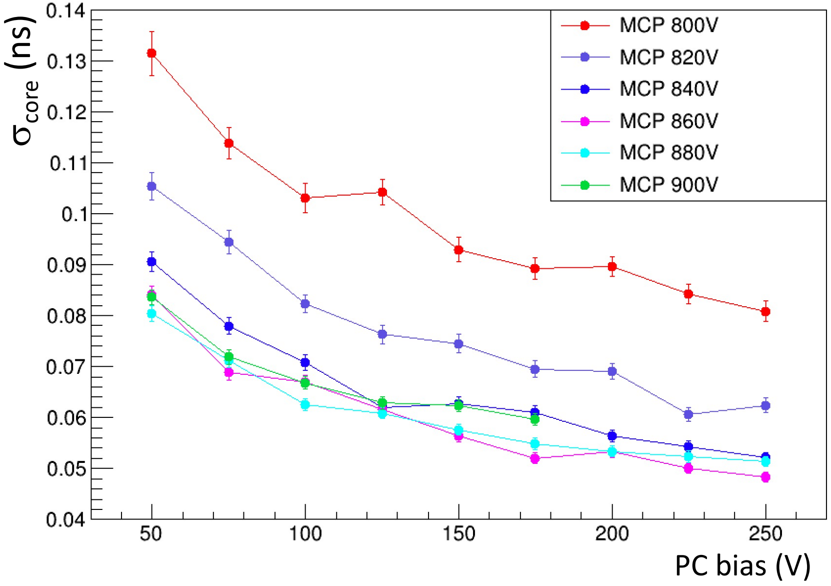
LAPPD Gen-II

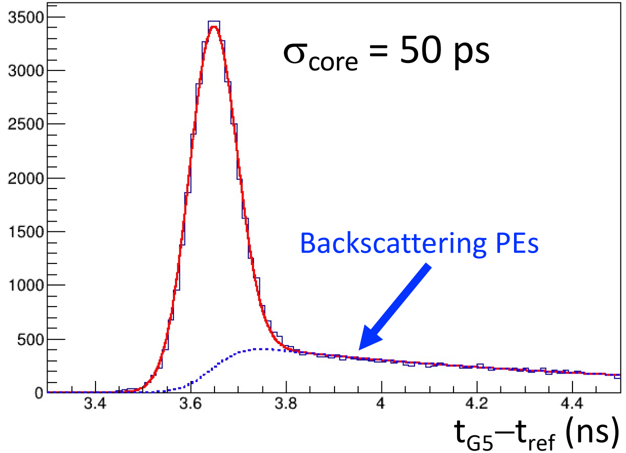


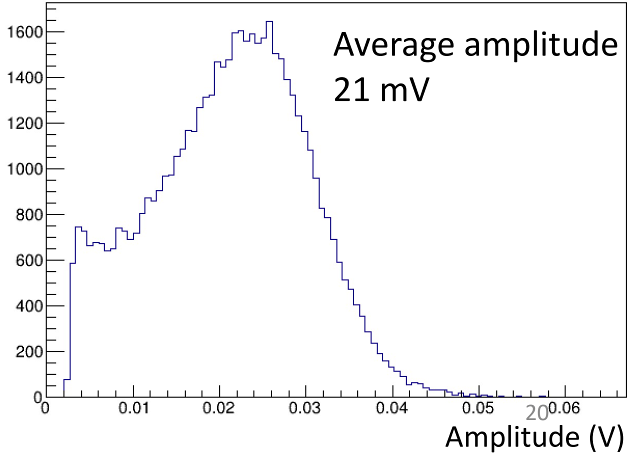
Reminder: Resistive interior anode with capacitively coupled external anode PCB with customizable pixel pattern

LAPPD Gen-II: single photoelectron

- **Two-dimensional voltage scan** is performed for both PC bias and MCP bias
  - Test performed illuminating the centre of one of the pixels
  - 200 V between MCPs and between bottom MCP and anode
  - Dependence of σ_{core} from PC bias

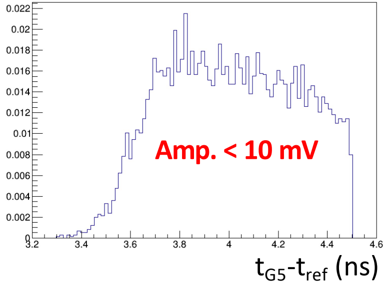


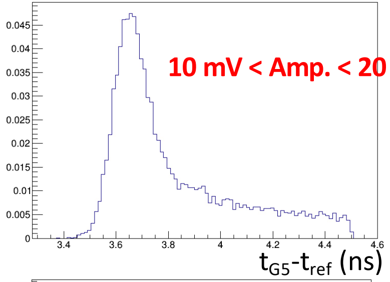


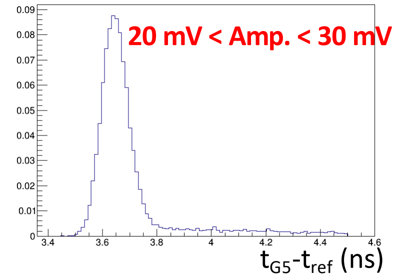


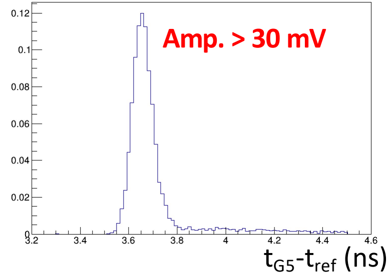
LAPPD Gen-II: backscattering PEs

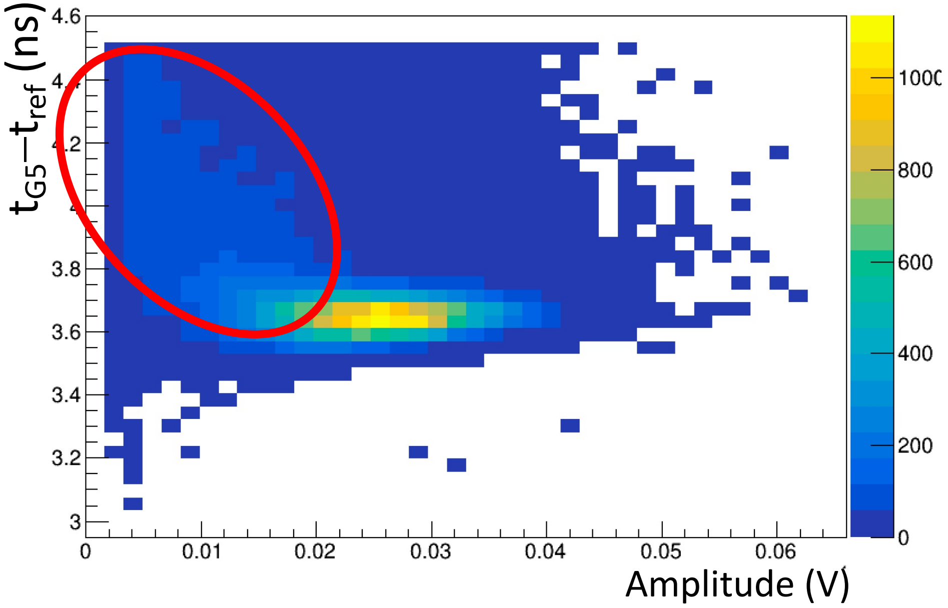
- Region with backscattered PE is mostly populated at **lower amplitudes**
  - The simple interpretation is that when hitting the MCP surface PE lose kinetic energy lowering the secondary electron yield
- Minimum requirement on amplitude removes a lot of backscattering







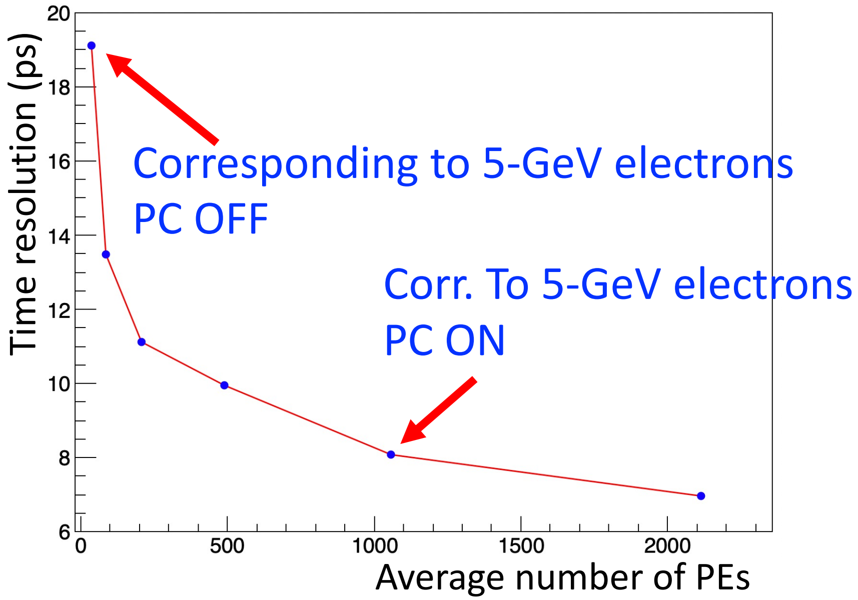


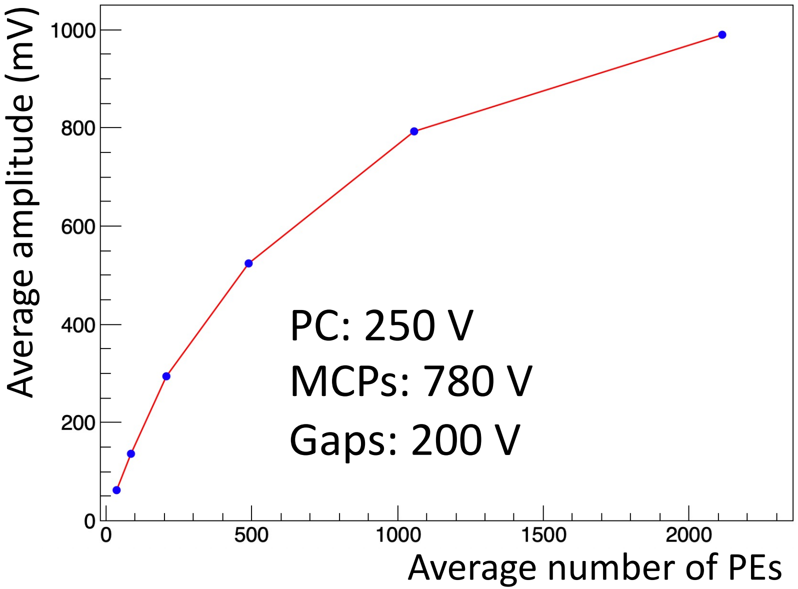


- E.g., **43% efficiency loss if amplitude > 20 mV**
- Lower PC bias ➔ lower backscattering fraction
  ➔ worse core time resolution
- **Find optimal working point depending on application**

LAPPD Gen-II: multiple PEs time resolution

- Defocused laser beam is used to reproduce PEs produced by the EM shower for 5 GeV electrons
- As for LAPPD Gen-I, fluctuations in the EM shower are not taken into account
- Note: laser is always pointing in the centre of a pixel



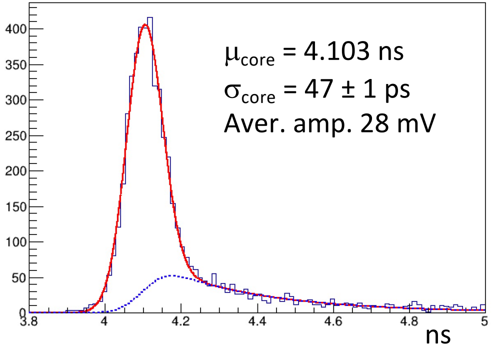


LAPPD Gen-II: effect of pixelated readout

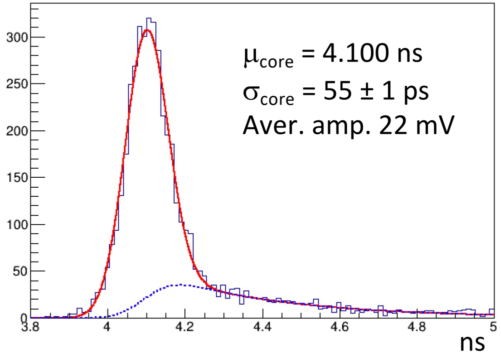
- The finite dimension of pixels (25 mm size) may introduce a TTS in the collection of the signal
  - Depending on where PEs hit the PC the time to collect the signal from the pixel may change
- Time resolution is measured for single PE
  - When laser beam is focused and hit the centre of the pixel
  - When laser beam is defocused into a spot with 25mm Ø with the spot centred on the pixel
  - Test repeated with 4 pixels

Example of one pixel

Focused laser



Defocused laser



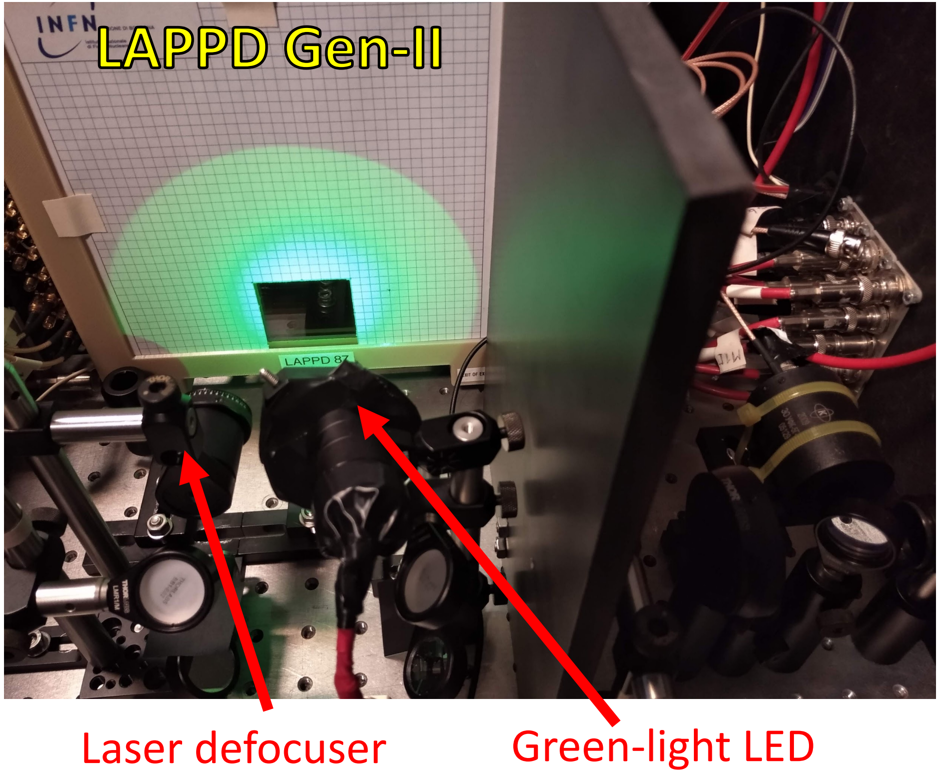
$$\sqrt{55^2 - 47^2} = 29 \pm 3 \text{ ps}$$

Averaging the effect over the 4 pixels, defocusing adds 24 ± 2 ps in quadrature to the focused-beam time resolution

No relevant effect on the mean value of the distribution μ_{core}

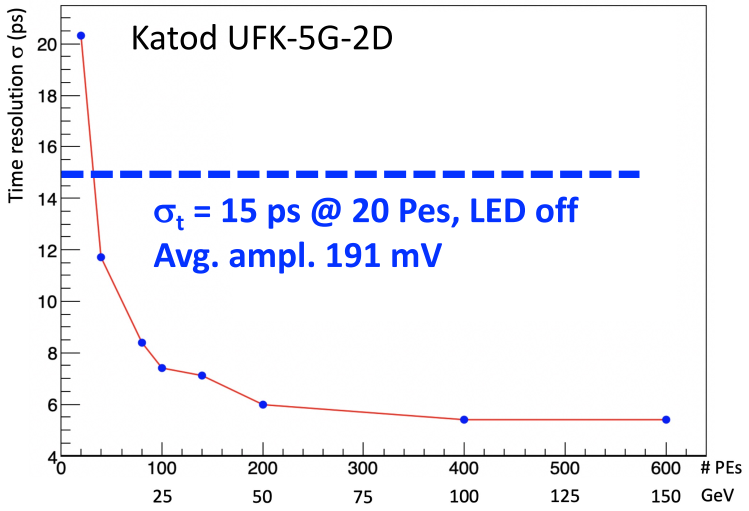
LAPPD Gen-II: realistic LHCb-U2 environment

- Simulations are used to reproduce realistic LHCb-U2 conditions
  - An LHCb ECAL module is placed in a region close to the beampipe and the number of charged particles per event entering the LAPPD device is estimated
  - **30 MHz/cm^2 of charged particles** are expected to traverse the LAPPD in central region
- Conditions are reproduced using
  - **Green LED** with power tuned to produce a rate of 30 MHz/cm^2 of PEs
  - **Defocused laser** pulse tuned to reproduce EM shower of electrons with different energies
- Same test is also conducted with Katod UFK-5G-2D MCP-PMT

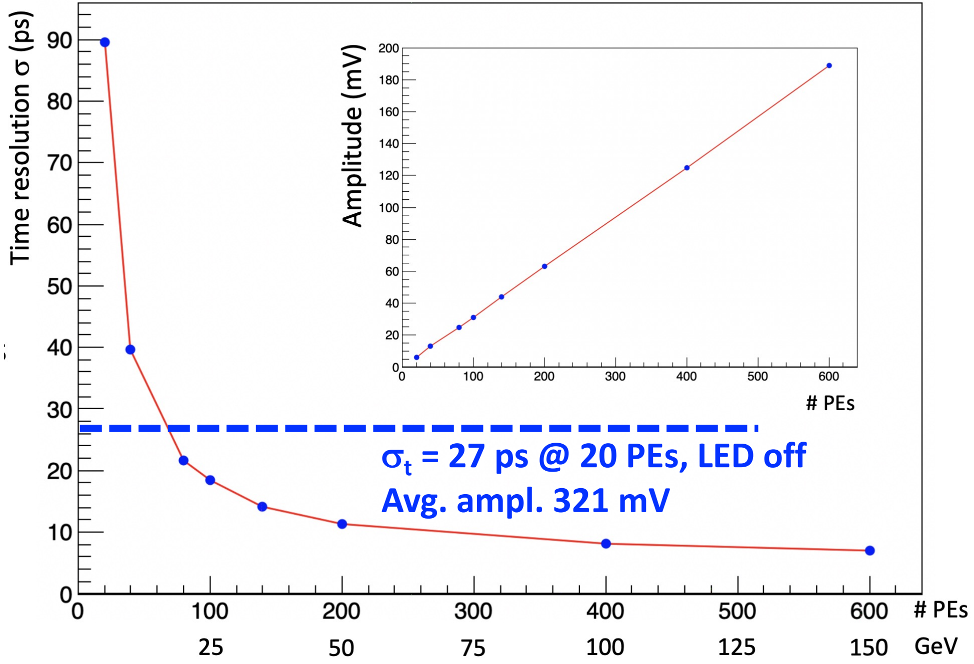


LAPPD Gen-II: realistic LHCb-U2 environment

- Below 80 PEs (roughly 20 GeV), the **time resolution degrades very rapidly** due to much suppressed signal amplitude
  - E.g., with 20 PEs the **amplitude goes from 321 to 6 mV**
- Katod UFK-5G-2D suffers much less thanks to smaller pore size (6 μm)
  - Average amplitude for 20 PEs goes from 191 to 24 mV



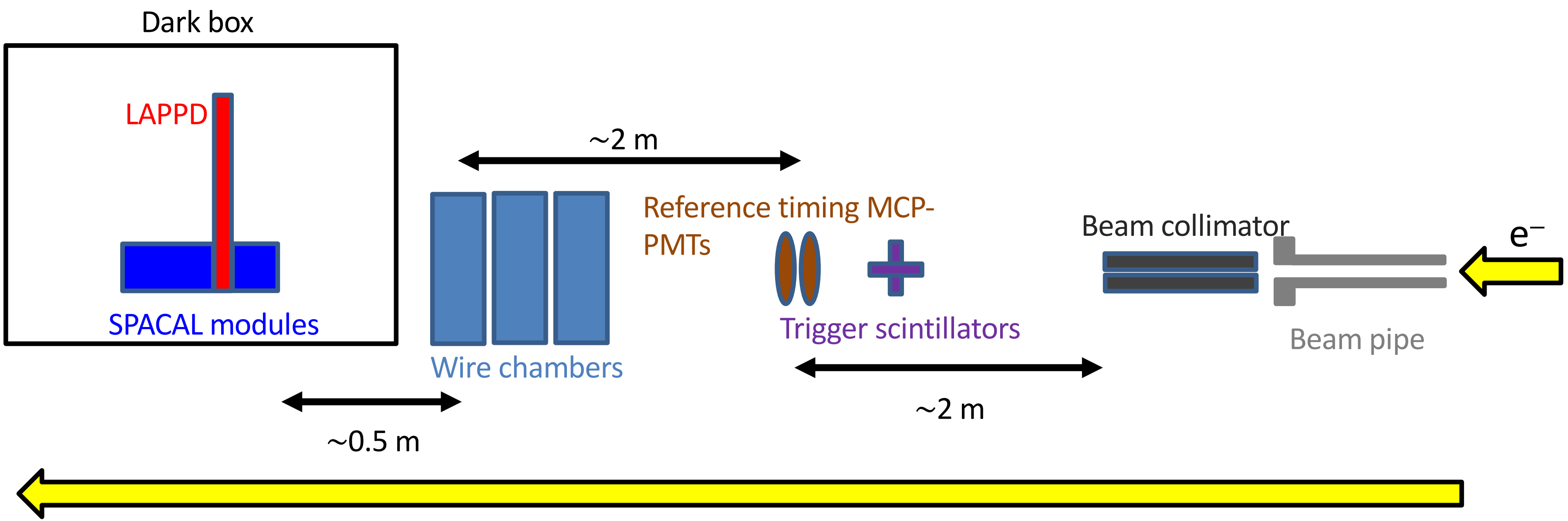
LAPPD Gen-II



DESY beamtests

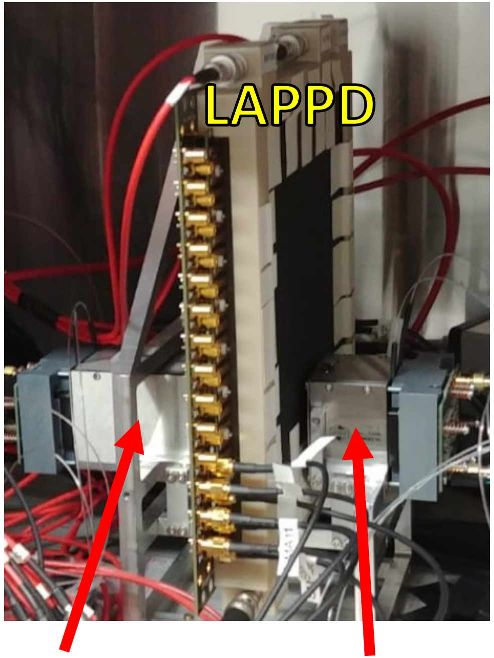
Experimental setup at DESY TB24

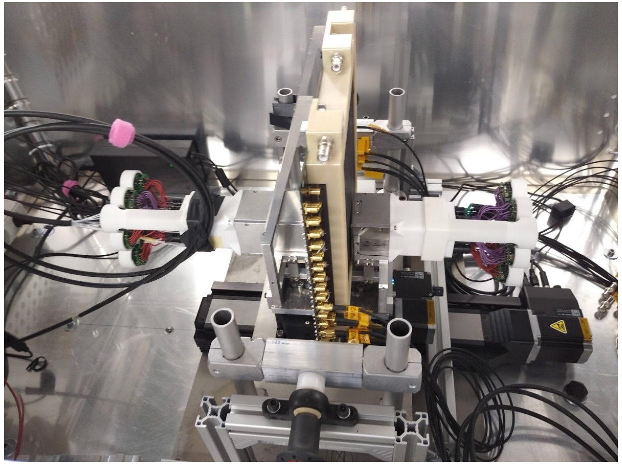
- SPACAL+LAPPD system can be rotated on the horizontal and azimuthal plane up to 6° with respect to beam direction
- Signals are digitised with the same CAEN v1742 board used in the lab
- Resolution of MCP-PMT timing reference is measured to be 12 ps

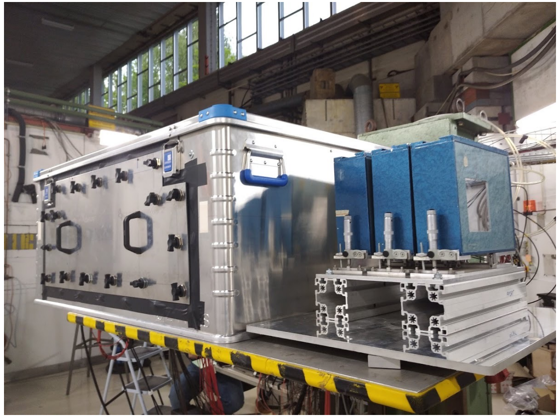


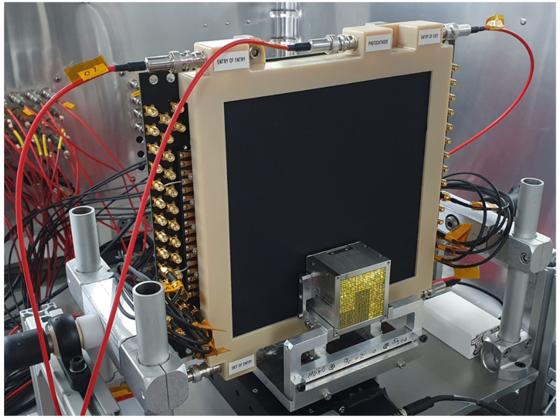
e⁻ beam direction (1, 2, 3, 4, 5 and 5.8 GeV)

Some picture of the experimental setup



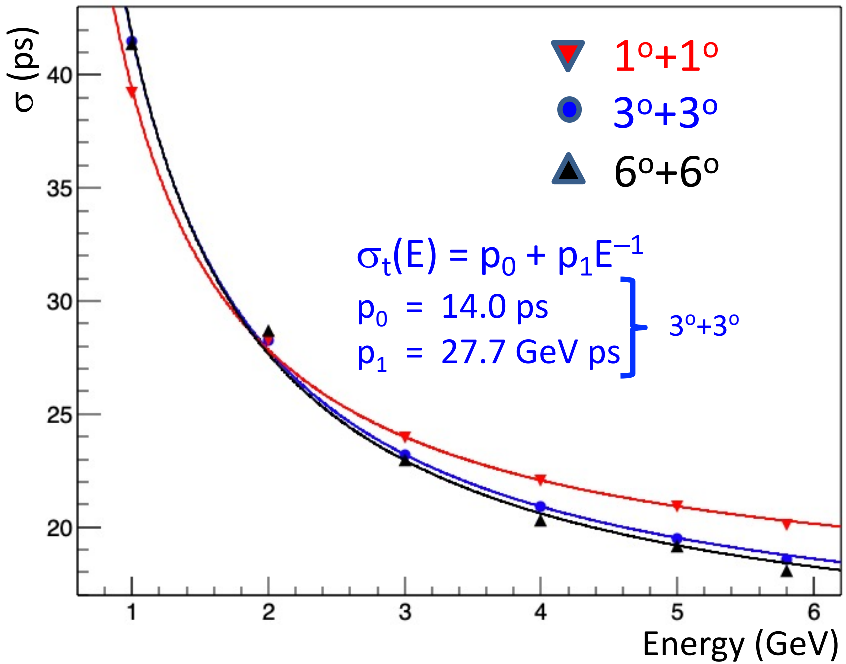






LAPPD Gen-I: time resolution with PC on

- Time resolution obtained after subtracting in quadrature 12 ps for the time reference MCPs (neglecting electronics jitter)
- **Best resolution at 5.8 GeV is 18.6 ps**
  - **Asymptotic** term at higher energies is **14.0 ps**
  - Consider this LAPPD has only 5% Q.E.
- Configuration with 1°+1° slightly worse



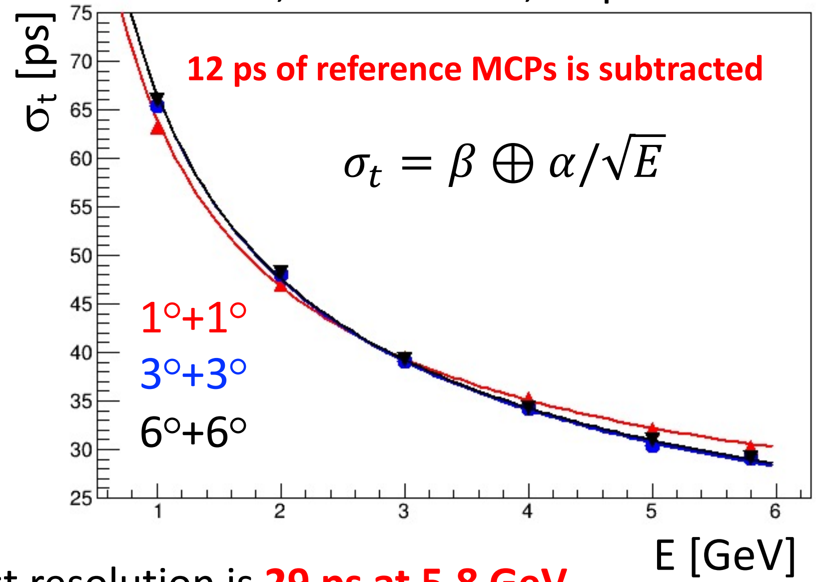
Voltage settings

PC: 400 V; MCP: 765 V; Gap: 200 V

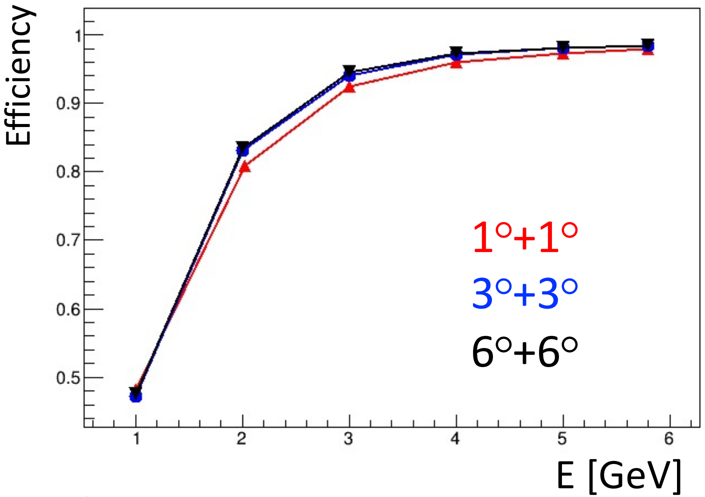
LAPPD Gen-I: time resolution with PC off

Voltage settings

PC: **-50 V**; MCP: 765 V; Gap: 200 V

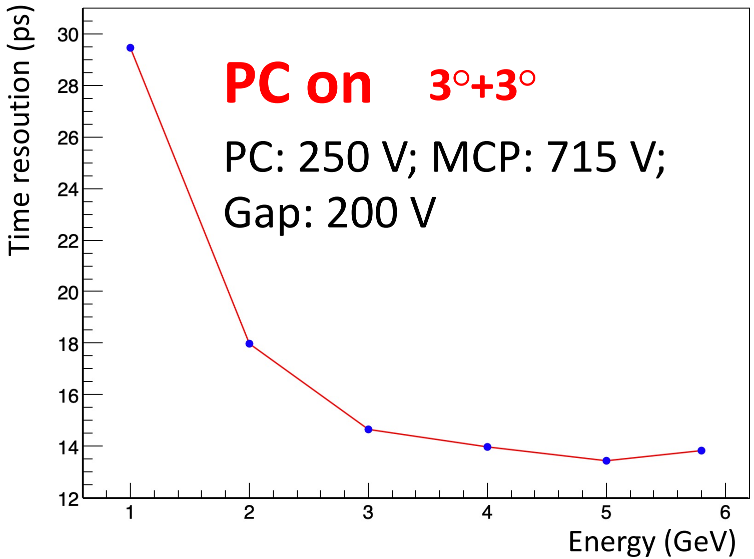


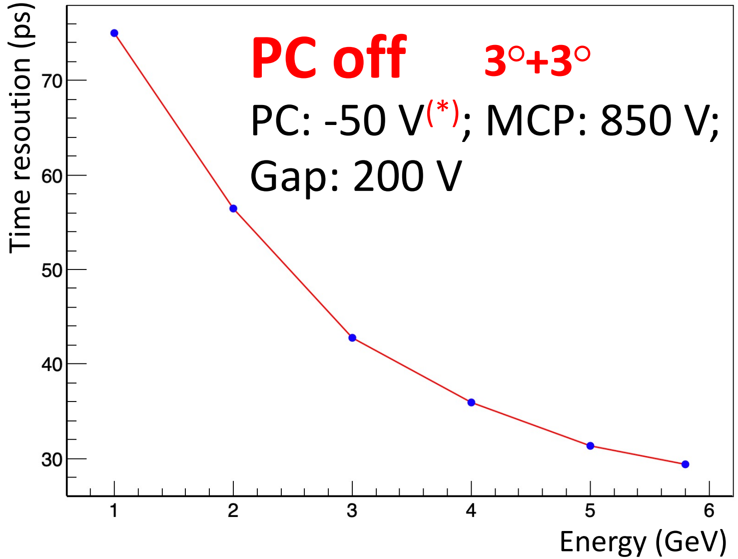
Angle	α	β
1°+1°	61.9 ± 0.3 ps $GeV^{0.5}$	16.5 ± 0.3 ps
3°+3°	66.2 ± 0.3 ps $GeV^{0.5}$	8.1 ± 0.6 ps
6°+6°	66.0 ± 0.3 ps $GeV^{0.5}$	9.3 ± 0.6 ps



- Best resolution is **29 ps at 5.8 GeV**
- Asymptotic term below 10 ps looks too good → range of energies too short
- **Drop of efficiency at lower energies** related to fluctuations of the number of charged particles in the EM shower

LAPPD Gen-II: time resolution





Only events with electrons impinging within 5 mm from the nominal centre of a pixel

- Best resolution for **PC on is 14 ps**
  - LAPPD Gen-II has much higher QE with respect to Gen-I ➔ 30% vs 5%
  - Time resolution is dominated by time spread of electromagnetic shower
- Best resolution with **PC off is slightly below 30 ps**
  - Additional spread due to fluctuations in the number of charged particles in the shower
  - Additional uncertainty in the position of first emitted electrons inside the MCP

Wrap-up and conclusions (I)

- A lot of work is being conducted to explore the possibility of building a **timing layer with O(10) ps precision for the LHCb-U2 ECAL**
  - The idea consists in placing a detector based on MCP between two sections of double readout sampling calorimeter split at the shower maximum
  - Sampling the secondary particles produced in EM showers will allow to measure time of arrival of γ and $e^{\pm}$ on the ECAL surface with the necessary precision
- The **LAPPD detector produced by Incom** has been identified as a promising solution
- Two LAPPDs have been extensively tested in the laboratory laser beam and at the DESY beamtest facility with high-energy electrons
- Laboratory studies indicate that working in high-rate environments will degrade the timing performances of LAPPD
  - Better performances are expected operating with MCPs with smaller pore sizes
  - Studies now being conducted with first 10 μm tiles

Wrap-up and conclusions (II)

- Results from beamtest conducted at DESY are encouraging but ultimate precision with PC off calls for improvements
  - Plenty of improvements still possible with an LHCb-optimised layout of the LAPPD
  - **Reducing pore sizes** from **20 to 10 μm** and MCP thickness will improve on time spread with PC off
  - **Adding a further MCP wafer** to the stack can also be helpful
- **New LAPPD with 10 μm pore sizes** just arrived in the lab
  - Will undergo an intensive testing program with laser beam and later with particle beam at the CERN SPS in November (higher energies than DESY)
- **Our warmest acknowledgments to Incom Inc. and Henry Frisch for their support, availability and guidance**

Summary of DESY results